

Deep Cumulus Convection in AM3

Leo Donner

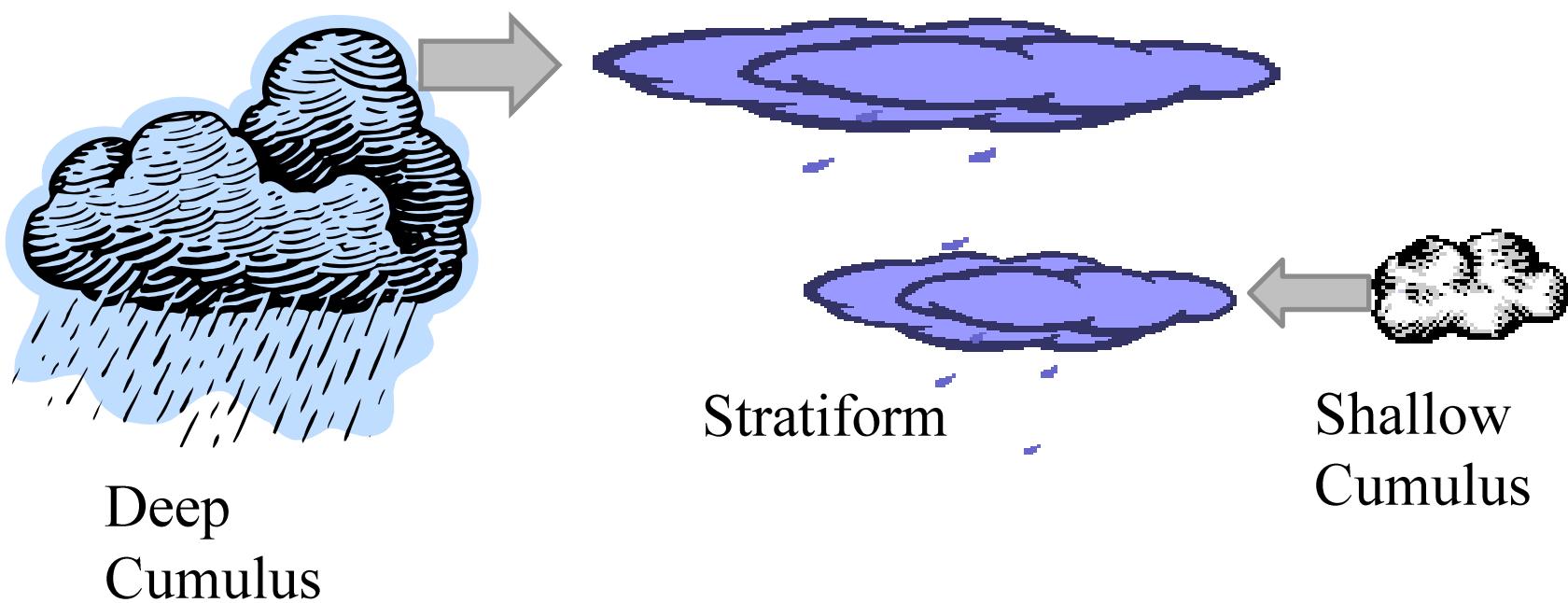
GFDL/NOAA, Princeton University

2012 GFDL Summer School

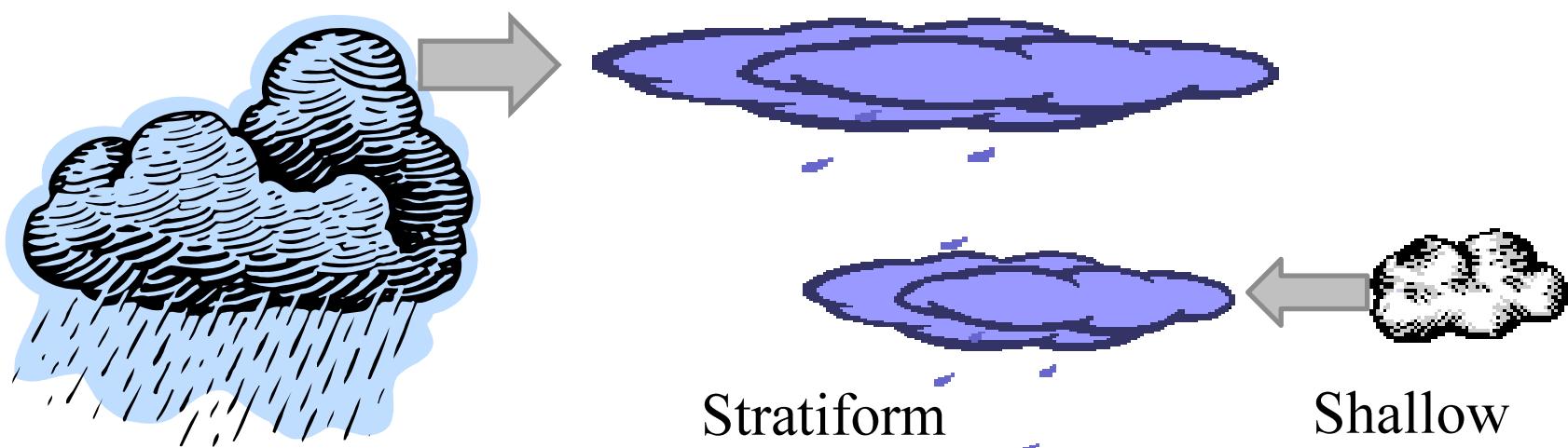
Overview

- Relationship of deep cumulus to other cloud systems in AM3
- General formulation of cumulus parameterization
- Mass-flux formulation and limitations
- Cells
- Mesoscale Updrafts and Downdrafts
- Characteristics of Cumulus Parameterization
- Behavior of Cumulus Parameterization in AM3

Relationship of Deep Cumulus to Other Cloud Systems in AM3



Relationship of Deep Cumulus to Other Cloud Systems in AM3



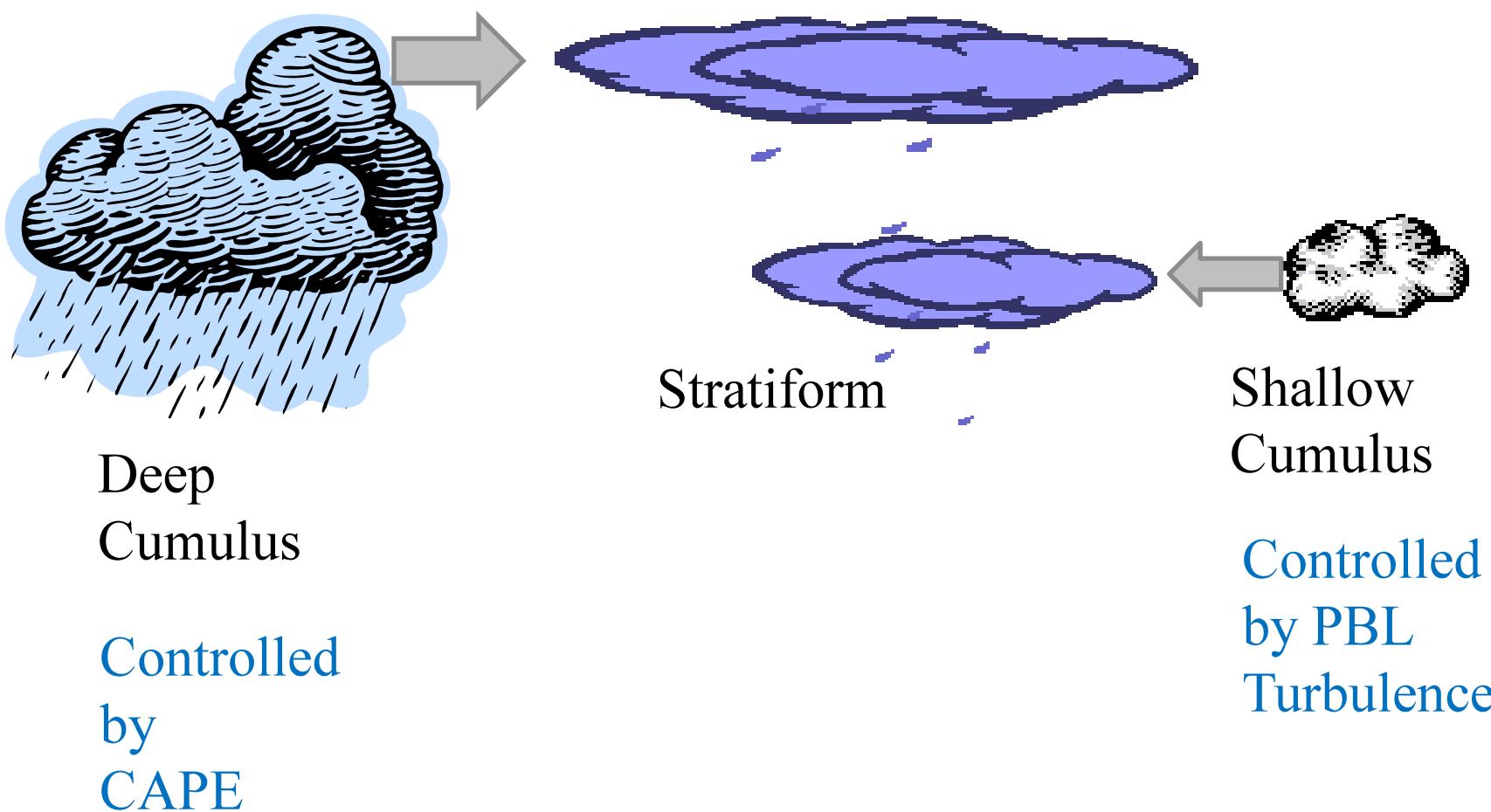
Deep
Cumulus

Controlled
by
CAPE

Stratiform

Shallow
Cumulus

Relationship of Deep Cumulus to Other Cloud Systems in AM3

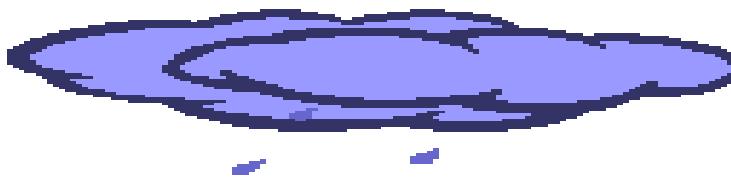


Relationship of Deep Cumulus to Other Cloud Systems in AM3



Deep
Cumulus

Controlled
by
CAPE



Stratiform

Evolve by Large-
Scale, Radiative,
Turbulent, and
Cumulus
Processes



Shallow
Cumulus

Controlled
by PBL
Turbulence

General Formulation of Cumulus Parameterization

- Large-Scale Effects of Cumulus Convection: Phase Changes and Eddy Fluxes
- Mass-Flux Approximation
- Limits of Mass-Flux Approximation
- Parameterizing Cumulus Vertical Velocities and Mesoscale Circulations

Effects of Cumulus Convection on Large-Scale Flow

Cumulus Parameterization Heat Source:

$$Q_\theta = \frac{\pi}{c_p} \sum_{P_i=1}^6 L_i \bar{\gamma}_i^* - \frac{\partial}{\partial p} \bar{\omega} \bar{\Theta}$$

Cumulus parameterization heat source is sum of phase changes in convective system and convergence of heat fluxes associated with convective system, including compensating subsidence.

The heat source can also be expressed as

$$Q_\theta = \frac{M_C}{p} \frac{\partial \bar{\theta}}{\partial z} + \frac{1}{p} \sum_{dc} D_i (\bar{\Theta}^*_{D_i} - \bar{\Theta}) + \frac{\pi}{c_p} (L_2 \bar{\gamma}_2^* + L_4 \bar{\gamma}_4^*)$$

Physically, the RHS is the sum of mass flux, detrainment, and evaporation terms.

NOTATION: γ_i condensation, evaporation, deposition, sublimation, freezing, and melting for $i = 1, \dots, 6$; M_C cumulus mass flux; D_i detrainment from i th detraining cloud (dc); π is ratio of potential temperature θ to temperature. Asterisk denotes convective-system process. $L_2 < 0, L_4 < 0$

Tracer Transport by Cumulus Convection

Cumulus Parameterization Tracer Source:

$$\rho Q_X = \rho \overline{S_X^*} - \frac{\partial}{\partial z} \overline{\rho w' X'}$$

Cumulus parameterization tracer source is sum of cumulus sources/sinks of tracer and convergence of tracer fluxes associated with convective system, including compensating subsidence.

The tracer source can also be expressed as

$$Q_X = \frac{M_C}{\rho} \frac{\partial}{\partial z} \bar{X} + \frac{1}{\rho} \sum_{dc} D_i (\bar{X}^*_{D_i} - \bar{X})$$

Physically, the RHS is the sum of mass flux and detrainment terms.

NOTATION: S_X denotes a source of the tracer X . M_C is the convective-system mass flux. D_i is the detrainment rate for the i th cloud element. Overbars refer to large-scale means. Primes are departures from the mean. Asterisks refer to in-cumulus values.

APPROXIMATIONS IN MASS-FLUX FORM

$$\frac{\partial \tilde{X}}{\partial t} = \frac{1}{\rho} \sum_{dc} D_i (X_i - \tilde{X}) + \left(\frac{M_c}{\rho} - \bar{w} \right) \frac{\partial \tilde{X}}{\partial z}$$

where \tilde{X} refers to the environment of the cloud ensemble, and \bar{w} refers to the large-scale mean.

$$\frac{\partial \bar{X}}{\partial t} = \frac{\partial}{\partial t} \sum \sigma_i X_i + \left(1 - \frac{\partial \sigma_c}{\partial t} \right) \tilde{X} + \left(1 - \sigma_c \right) \frac{\partial \tilde{X}}{\partial t}$$

$$\tilde{X} = - \frac{\sum \sigma_i X_i}{(1 - \sigma_c)} + \frac{\bar{X}}{(1 - \sigma_c)}$$

If $\bar{X} = \tilde{X}$,

$$\frac{d\bar{X}}{dt} = \frac{1}{\rho} \sum_{dc} D_i (X_i - \bar{X}) + \frac{M_c}{\rho} \frac{\partial \bar{X}}{\partial z}$$

Robustness of Mass-Flux Approximation

- Approximation requires cumulus fraction small (scale separation).
- Approximation does NOT require small number of members in cumulus ensemble.
- Approximation does NOT assume cumulus updrafts produce LOCAL, i.e., within grid box, subsidence.
- Total cumulus mass flux plays central role, regardless of ensemble size.

Limitations of Mass-Flux Approach: Scale-Separated Flow

- Simplification to single parameter M_c lost if detrainment and evaporation are important and are not simple functions of M_c .
- Detrainment calculation becomes complex. Additional parameters must be introduced, which depend on details of cumulus spectrum.
- Evaporation terms require knowledge of cumulus microphysics, cumulus vertical velocities, and their distributions in the cumulus ensemble.
- Aerosol activation, critical for study of aerosol indirect effect, depends on cumulus vertical velocity.

Beyond Mass Fluxes: Cumulus Vertical Velocities, Microphysics, and Aerosols

Use ensemble of cumulus cells, each member characterized by entrainment rate μ , temperature T_c , area a , mixing ratio q_c :

$$\frac{dT_c}{dz} = f_1(T_c, \bar{T}, q_c, \bar{q}, \mu)$$

$$\frac{dw_c}{dz} = f_2(T_c, \bar{T}, w_c, \mu, \text{microphysics})$$

$$\frac{1}{\rho a w_c} \frac{d}{dz}(\rho a w_c) = \mu$$

Beyond Mass Fluxes: Cumulus Vertical Velocities, Microphysics, and Aerosols

Use ensemble of cumulus cells, each member characterized by entrainment rate μ , temperature T_c , area a , mixing ratio q_c :

$$\frac{dT_c}{dz} = f_1(T_c, \bar{T}, q_c, \bar{q}, \mu) \quad \leftarrow \text{Saturated Adiabatic Ascent, Entrainment}$$

$$\frac{dw_c}{dz} = f_2(T_c, \bar{T}, w_c, \mu, \text{microphysics})$$

$$\frac{1}{\rho a w_c} \frac{d}{dz}(\rho a w_c) = \mu$$

Beyond Mass Fluxes: Cumulus Vertical Velocities, Microphysics, and Aerosols

Use ensemble of cumulus cells, each member characterized by entrainment rate μ , temperature T_c , area a , mixing ratio q_c :

$$\frac{dT_c}{dz} = f_1(T_c, \bar{T}, q_c, \bar{q}, \mu) \quad \text{Saturated Adiabatic Ascent, Entrainment}$$

$$\frac{dw_c}{dz} = f_2(T_c, \bar{T}, w_c, \mu, \text{microphysics}) \quad \text{Buoyancy, Entrainment, Condensate Loading}$$

$$\frac{1}{\rho a w_c} \frac{d}{dz} (\rho a w_c) = \mu$$

Closure

1. Relative numbers n_i and n_j of cells with entrainment rates μ_i and μ_j , radii R_i and R_j :

$$\frac{a_j}{a_i} = \frac{n_j}{n_i} \frac{R_j^2}{R_i^2}$$

Ratios $\frac{n_j}{n_i}$ and $\frac{R_j}{R_i}$ from LeMone and Zipser (1980, *J. Atmos. Sci.*) observations and inverting equation for w_c (Donner, 1993, *J. Atmos. Sci.*)

Closure

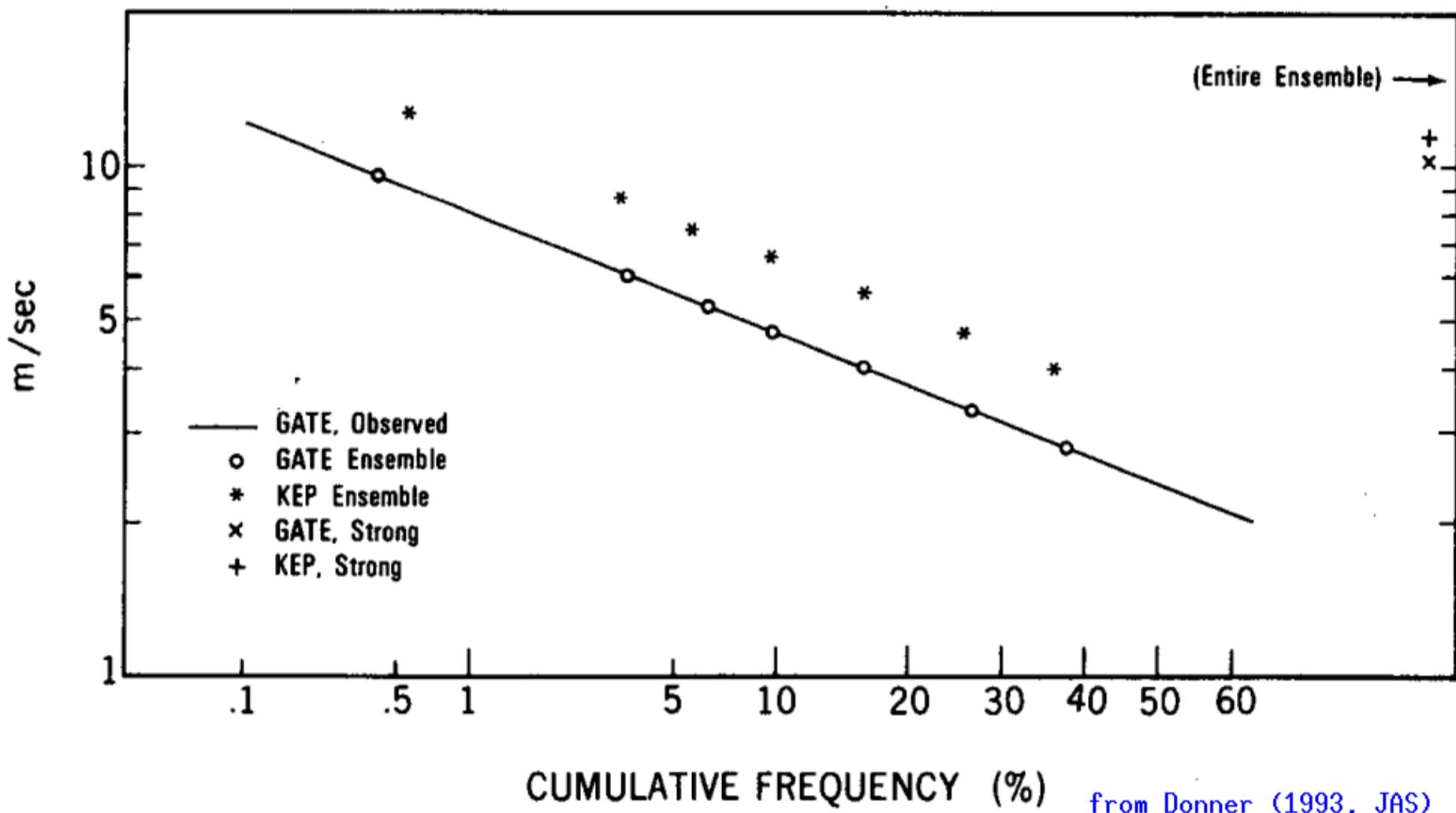
1. Relative numbers n_i and n_j of cells with entrainment rates μ_i and μ_j , radii R_i and R_j :

$\frac{a_j}{a_i} = \frac{n_j}{n_i} \frac{R_j^2}{R_i^2}$ Ratios $\frac{n_j}{n_i}$ and $\frac{R_j}{R_i}$ from LeMone and Zipser (1980, *J. Atmos. Sci.*) observations and inverting equation for w_c (Donner, 1993, *J. Atmos. Sci.*)

2. Total mass flux:

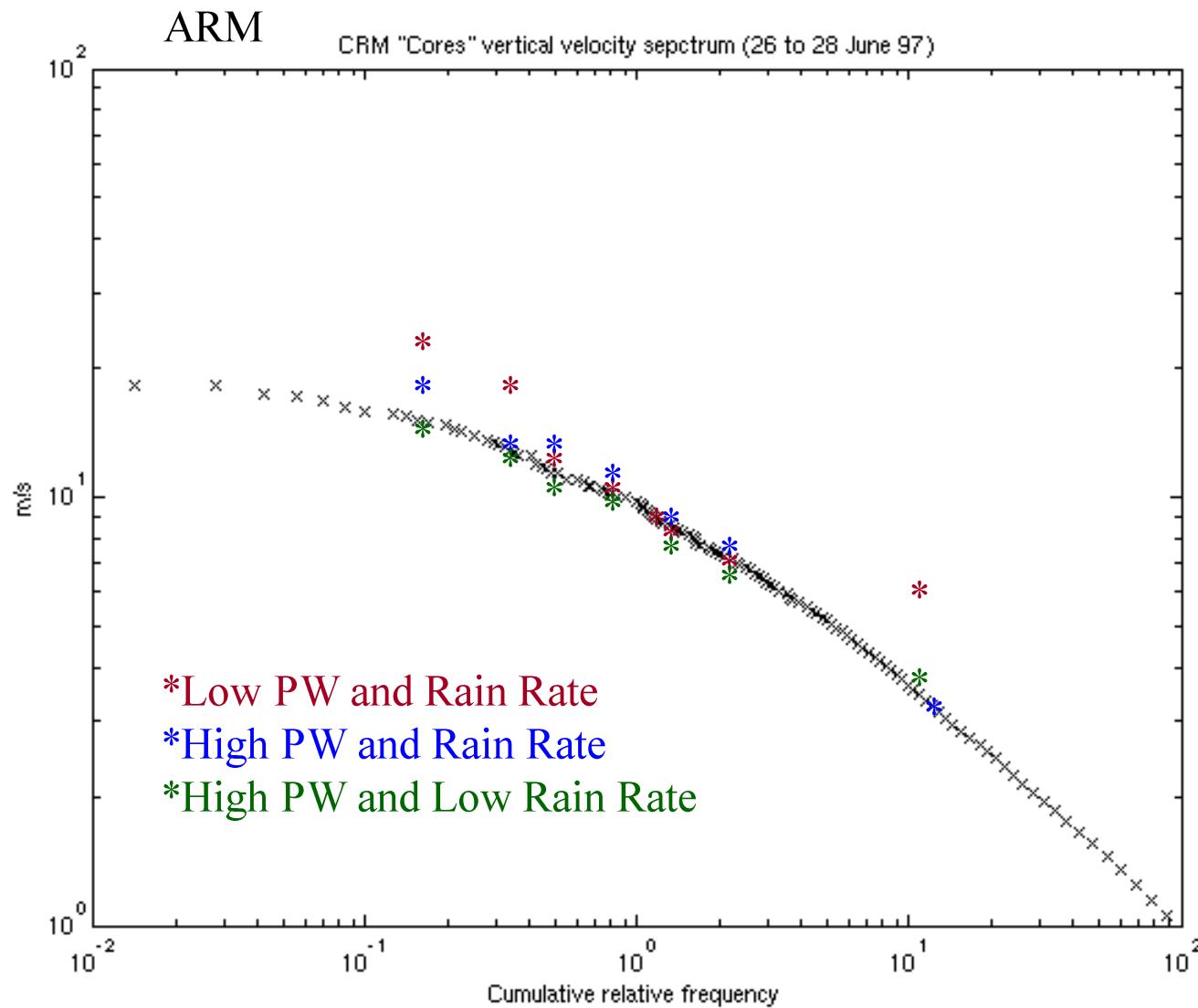
$\frac{CAPE - CAPE_0}{\tau} = a_1(p_b)I_1$, where $CAPE$ is convective available potential energy and I_1 is function of normalized cumulus heating and moistening profiles (Donner *et al.*, 2001, *J. Climate*).

VERTICAL-VELOCITY SPECTRA



from Donner (1993, JAS)

CRM results provide independent evaluation of entrainment PDF



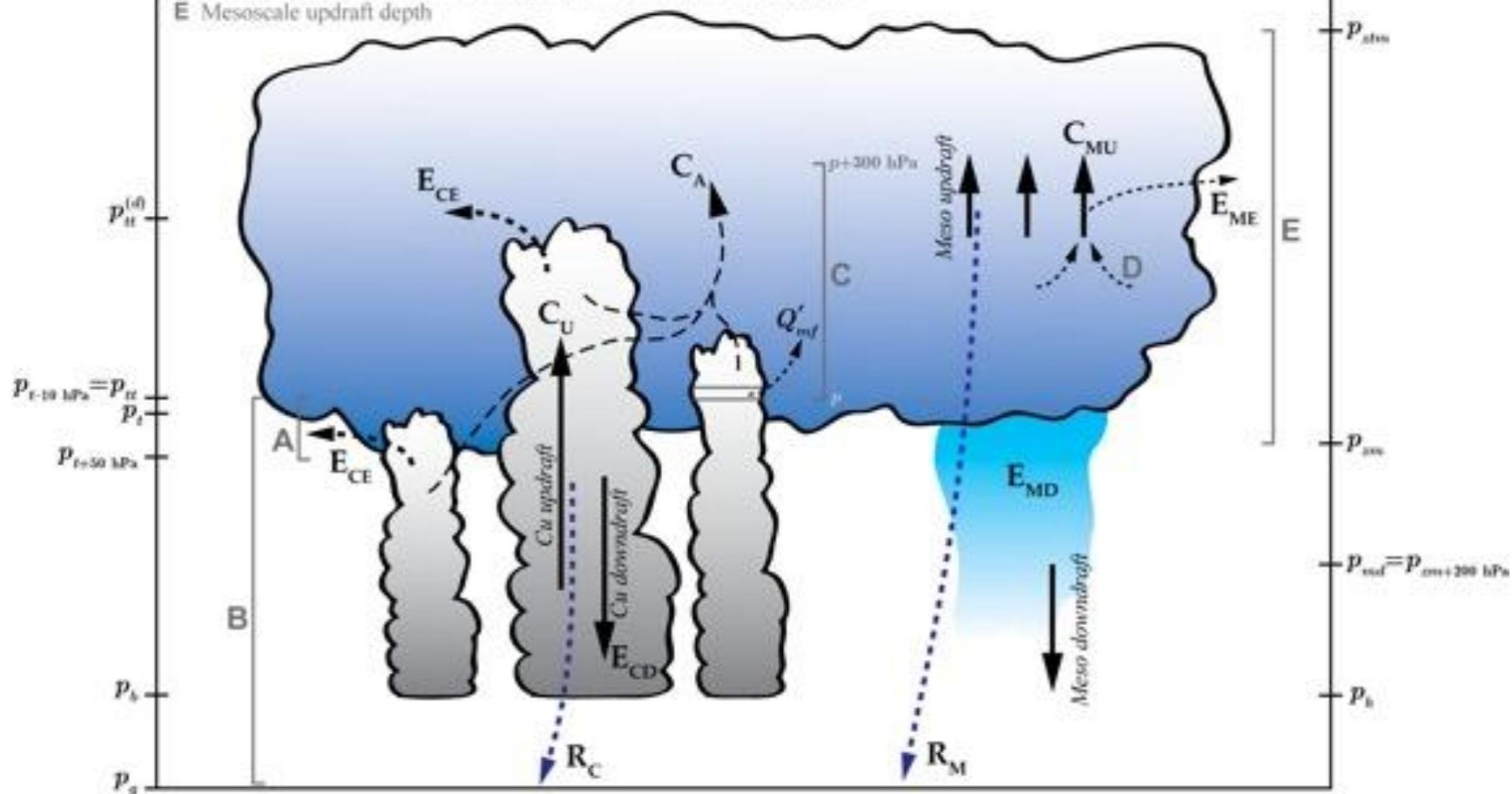
CRM results from Cris Batstone, CDC; *,*,* from Donner (1993) entrainment PDF

Mesoscale Updrafts and Downdrafts

- Mesoscale updraft redistributes vapor detrained from cells, deposits vapor to ice, and detrains mass and ice to large-scale clouds. Horizontal area is proportional to total cell area and mesoscale updraft base where cells begin to detrain.
- Sublimation and evaporation occur in mesoscale and convective scale downdrafts.
- Mesoscale liquid and ice are detrained from convective cells, with empirical partition among mesoscale components.

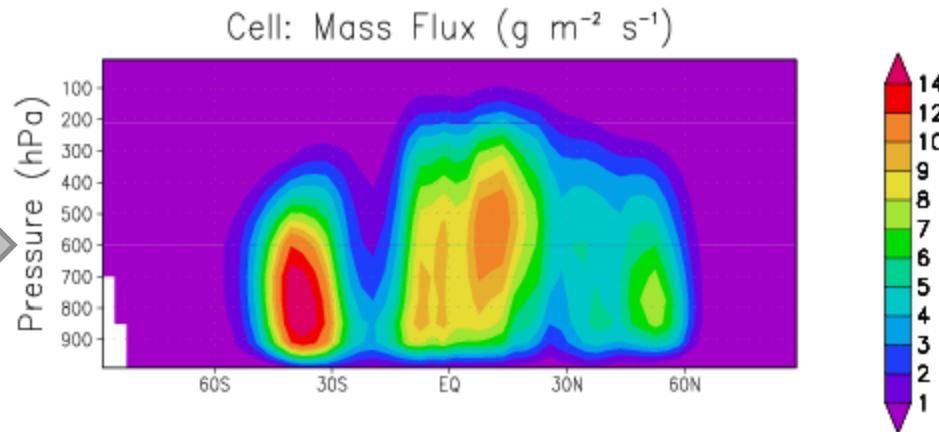
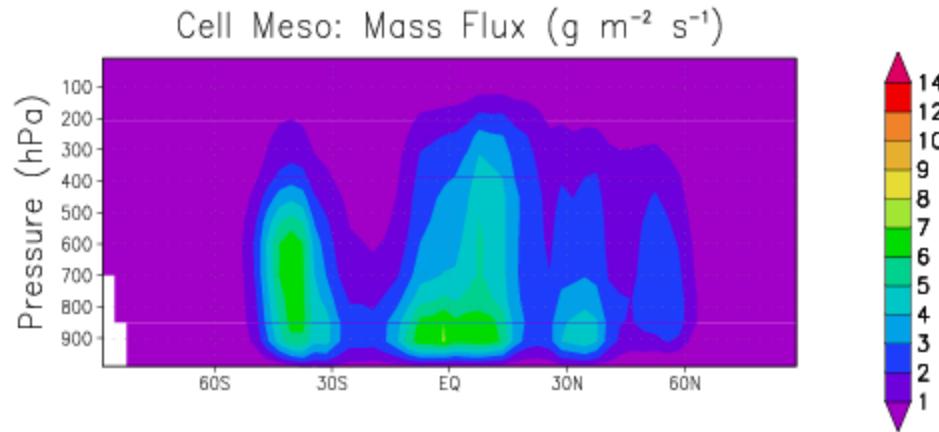
Donner Deep Convection Scheme

- A Uniform distribution of E_{CE} , evaporation from cumulus updrafts
- B Uniform distribution of E_{CD} , evaporation in cumulus downdrafts
- C Uniform distribution of water vapor, provided by cumulus updrafts, available to mesoscale clouds
- D Water vapor in cumulus environment advected by mesoscale updrafts
- E Mesoscale updraft depth



from Benedict et al. (2012, *J. Climate*, in press)

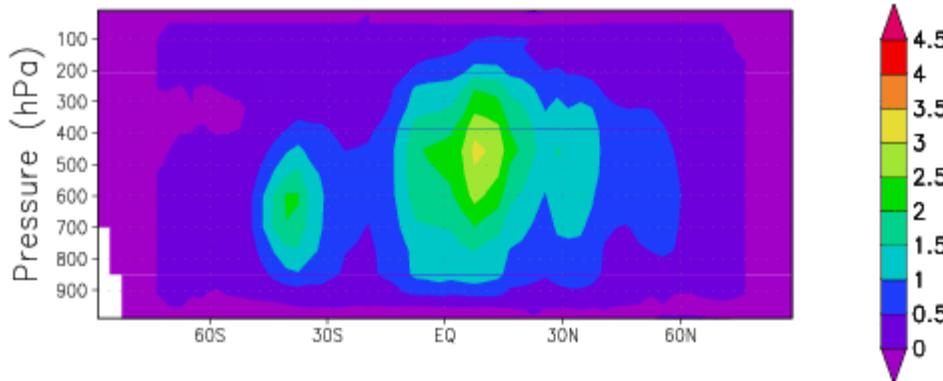
MESOSCALE CIRCULATIONS: IMPLICATION FOR MASS FLUXES AND TRACER TRANSPORT



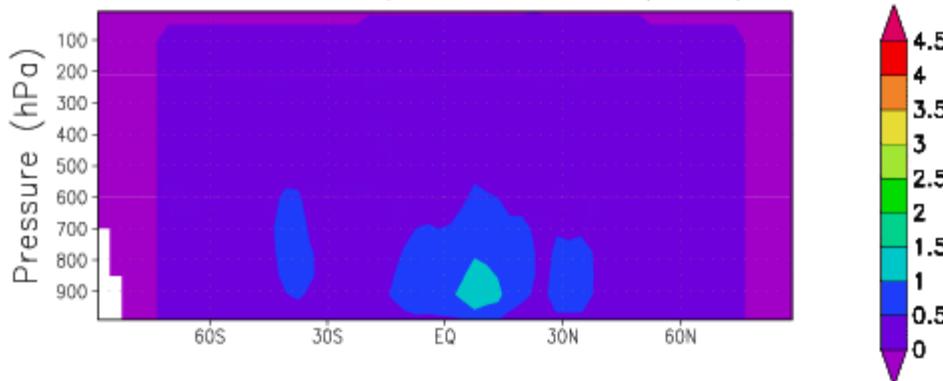
De-activate
mesoscale
updrafts
and
downdrafts



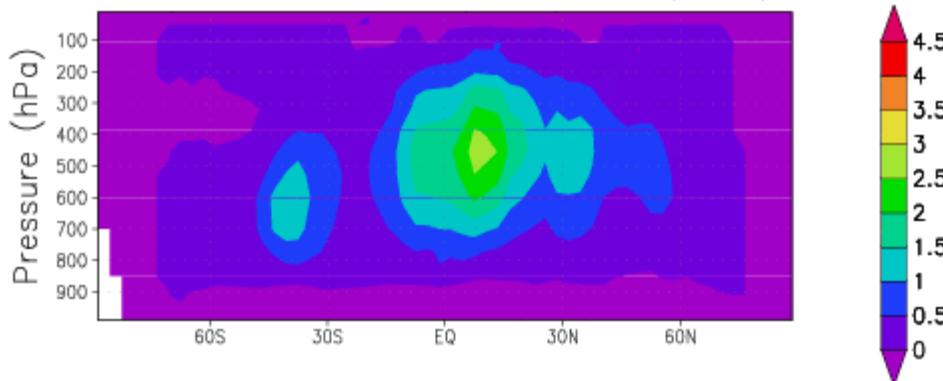
Cell Meso: Mass Flux+Detrainment Terms ($K \text{ d}^{-1}$)



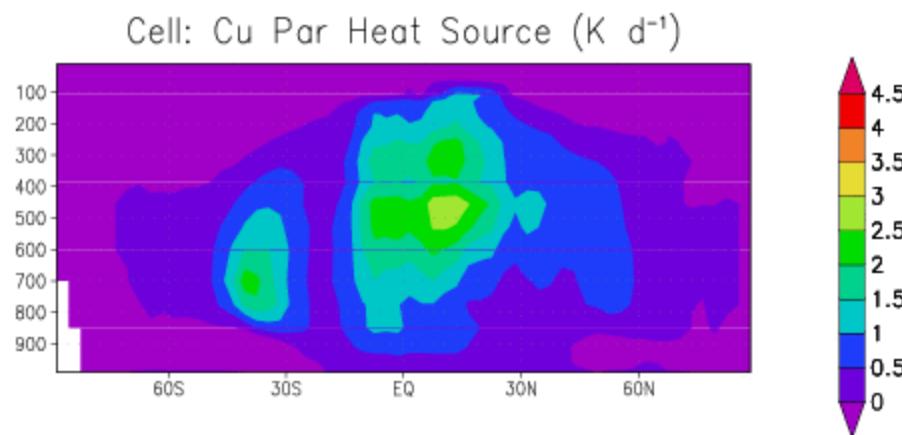
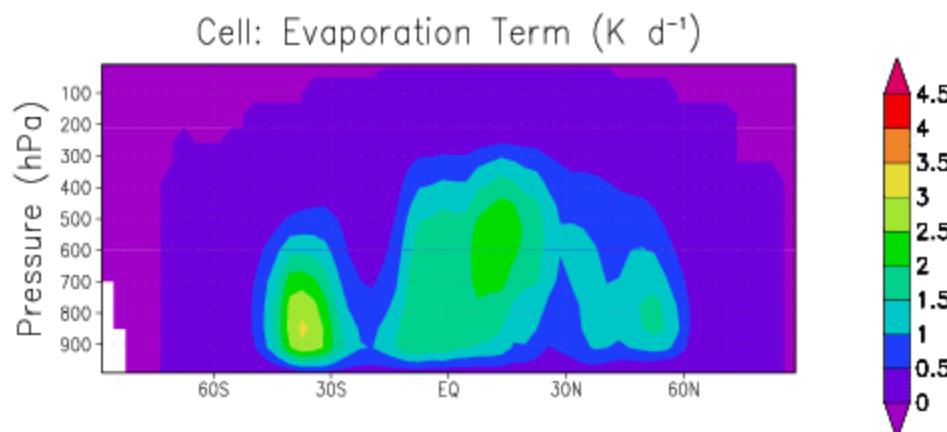
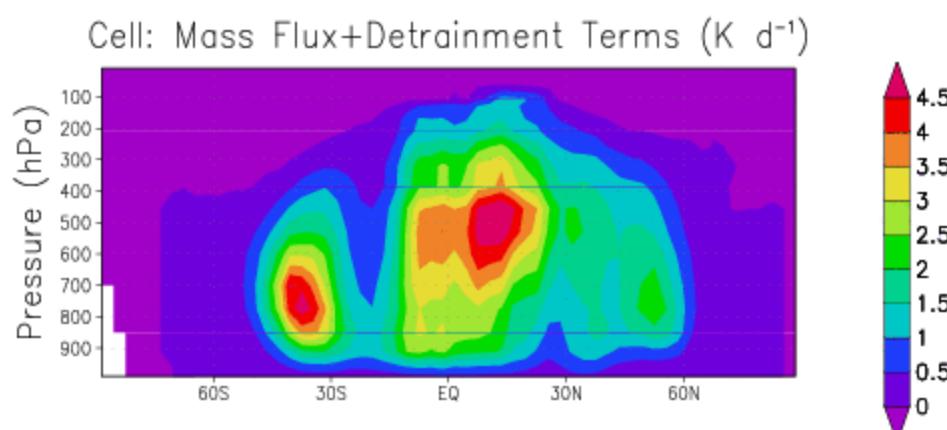
Cell Meso: Evaporation Term ($K \text{ d}^{-1}$)



Cell Meso: Cu Par Heat Source ($K \text{ d}^{-1}$)

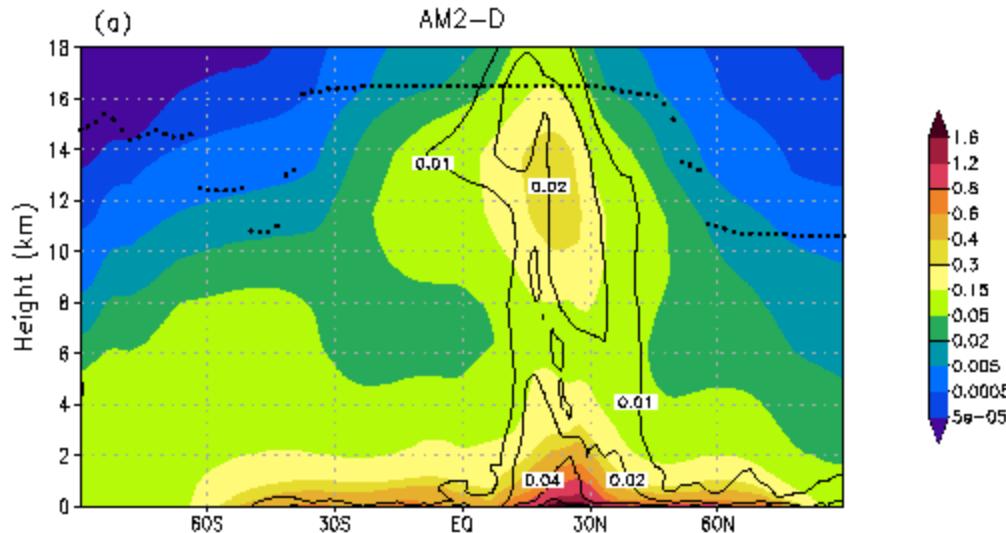


De-activating mesoscale increases both mass flux and evaporation, but total heating does not change much.
Closure enforces total heating but not mass flux.

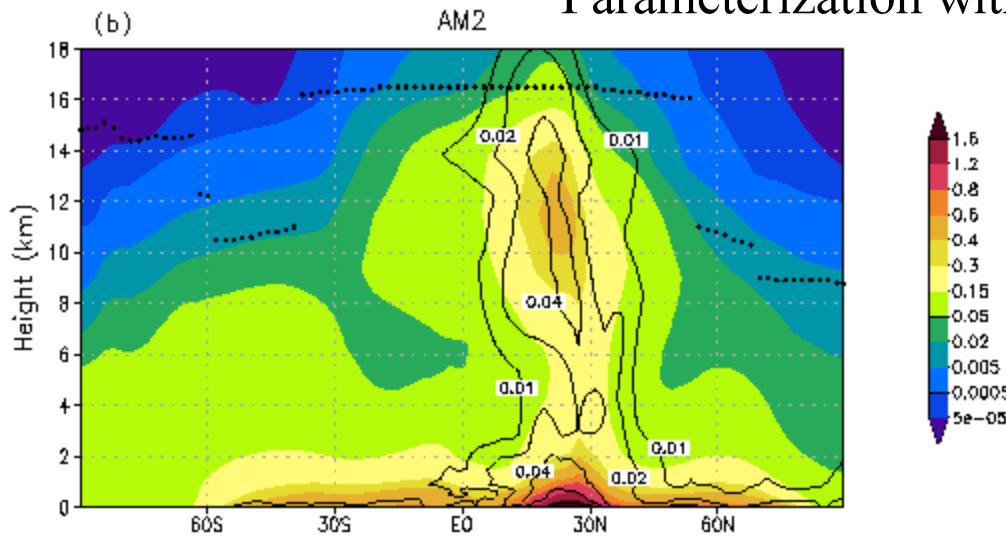


Methyl iodide (10^{-12} volume mixing ratio)
August–September

Cumulus Parameterization with Mesoscale Circulation



Parameterization with Cells Only

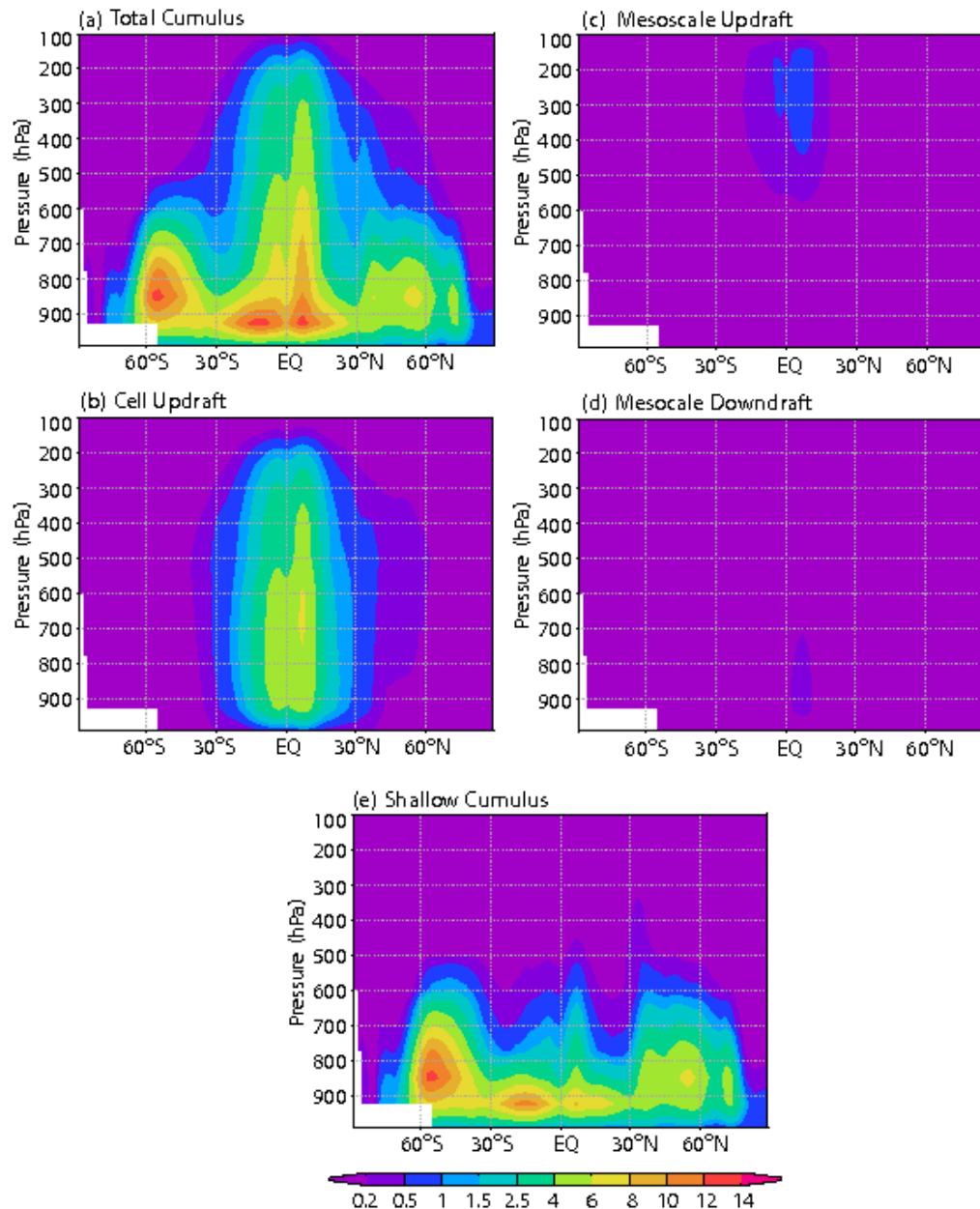


Solid lines
indicate
standard
deviations.

from
Donner et
al. (2007,
JGR)

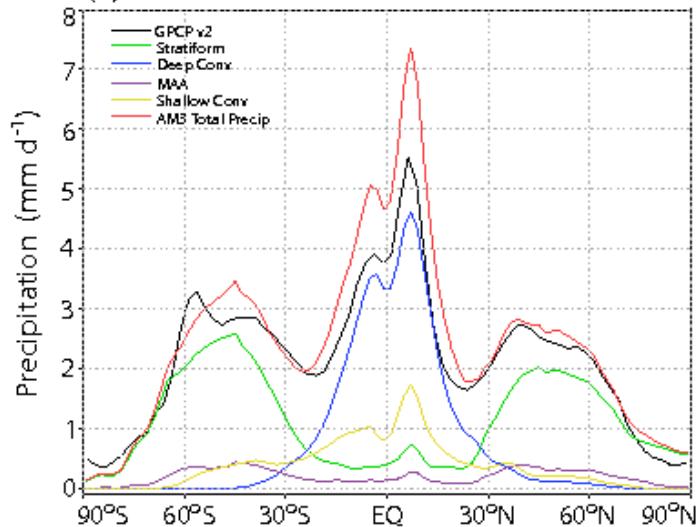
CUMULUS CONVECTION IN AM3 AND CM3

Mass Flux ($\text{g m}^{-2}\text{s}^{-1}$)

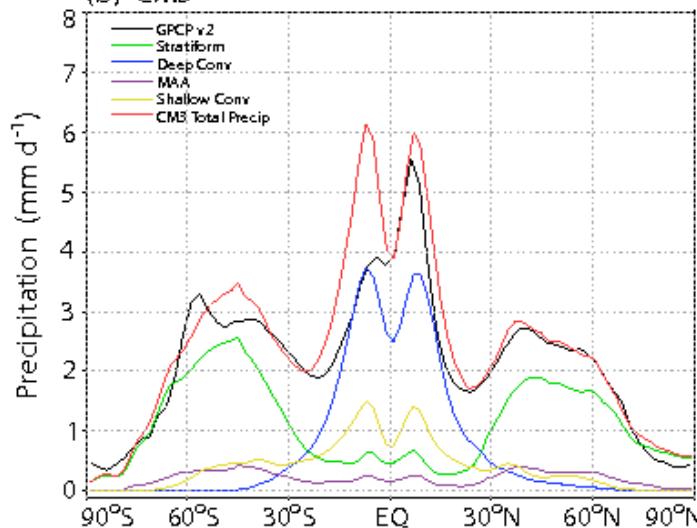


Annual Precipitation

(a) AM3

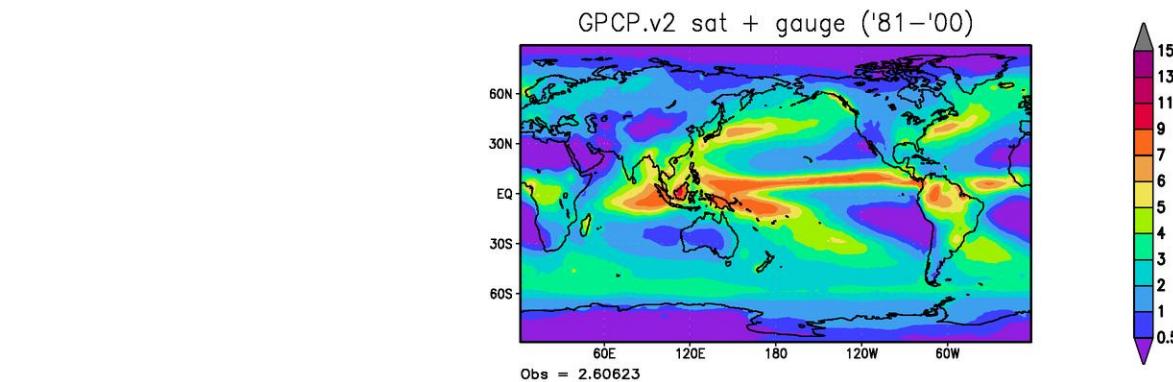


(b) CM3

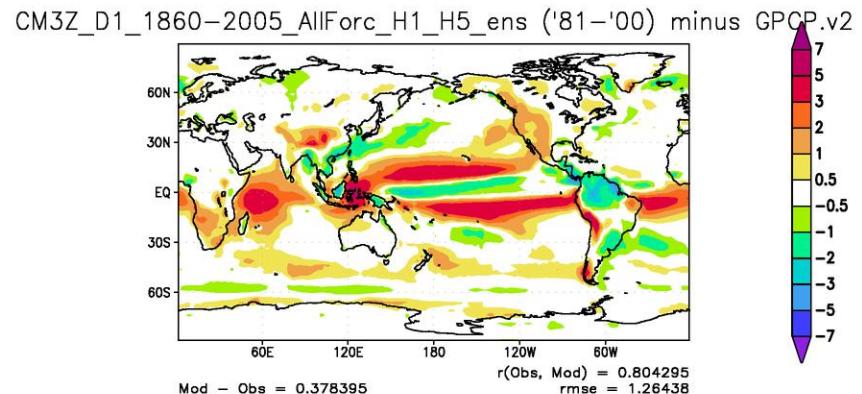
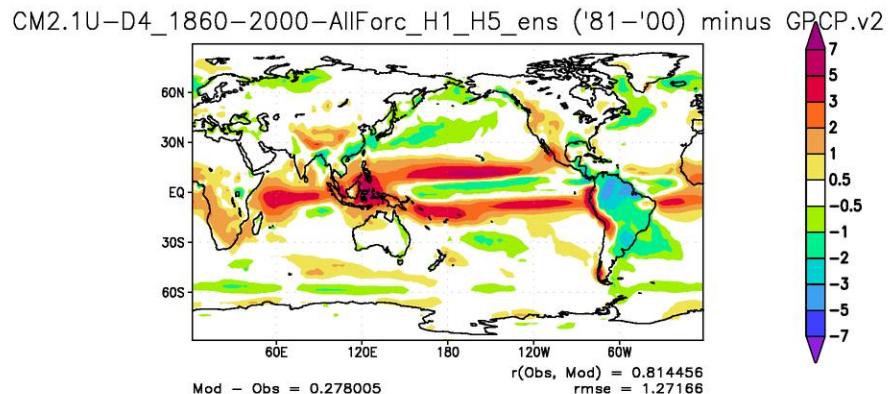
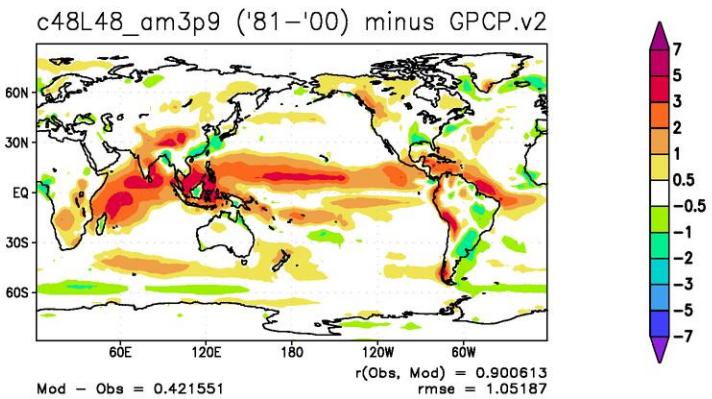
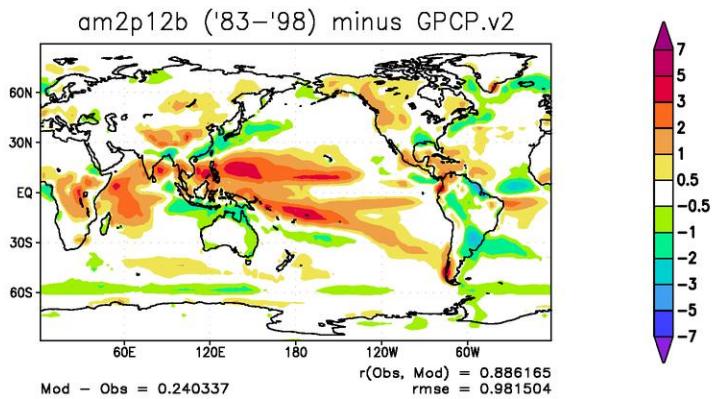


Kato et al. (2011, *J. Geophys. Res.*) indicate GPCP precipitation may be biased 15% to 20% low.

ANN PRECIP (mm/d)



Kato et al. (2011, *J. Geophys. Res.*) indicate GPCP precipitation may be biased 15% to 20% low.



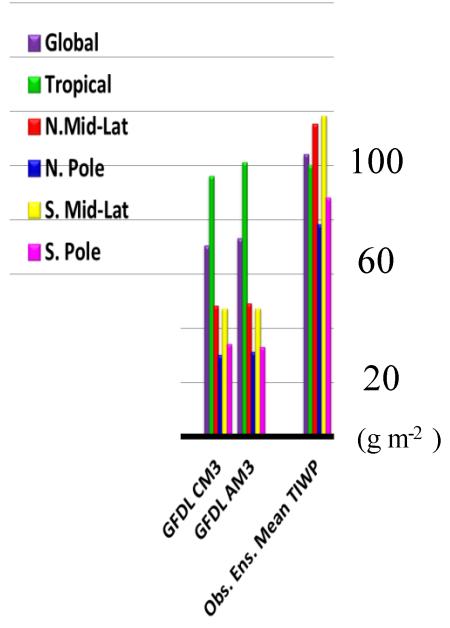
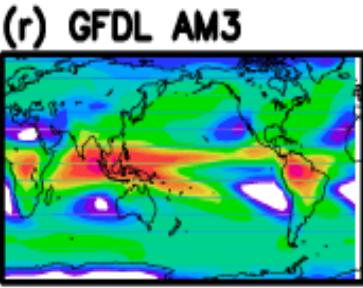
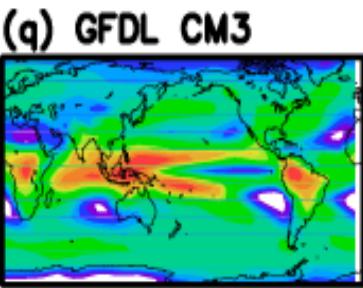
GPCP.v2:

<http://www.cdc.noaa.gov/cdc/data.gpcp.html>

Adler et al., Journal of Hydrometeorology, December 2003, p. 1147–1167

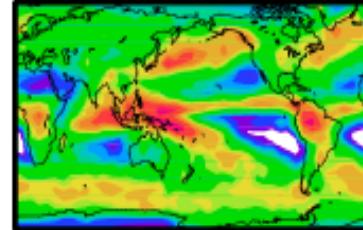
ICE WATER PATH

from Li *et al.* (2012,
J. Geophys. Res., in
press)

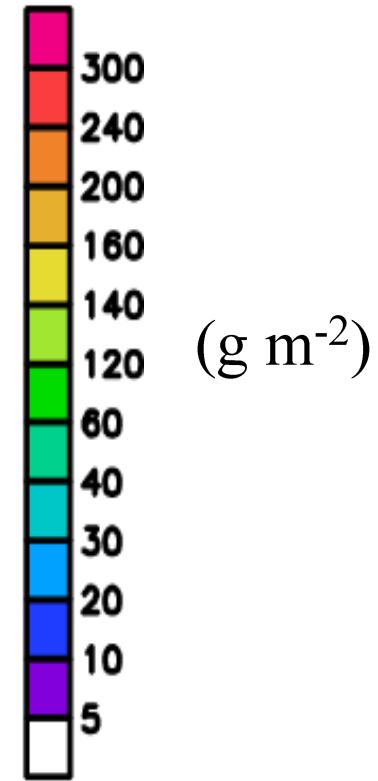
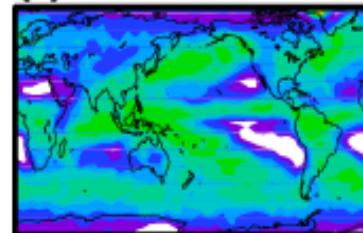


Obs from CloudSat-only,
CloudSat-CALIPSO DARDAR,
CloudSat-CALIPSO 2C-ICE.
DARDAR and 2C-ICE use different
particle size assumptions.

(w) Obs Ens Mean TIWP

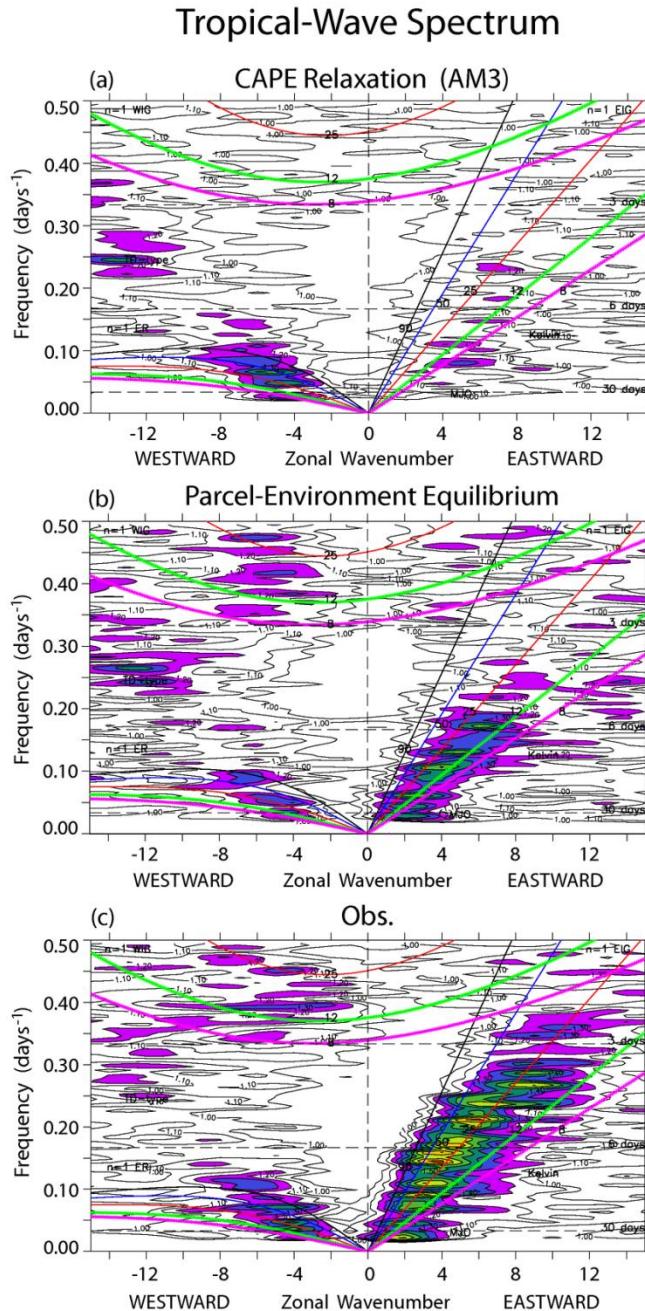


(x) Obs Ens Std TIWP



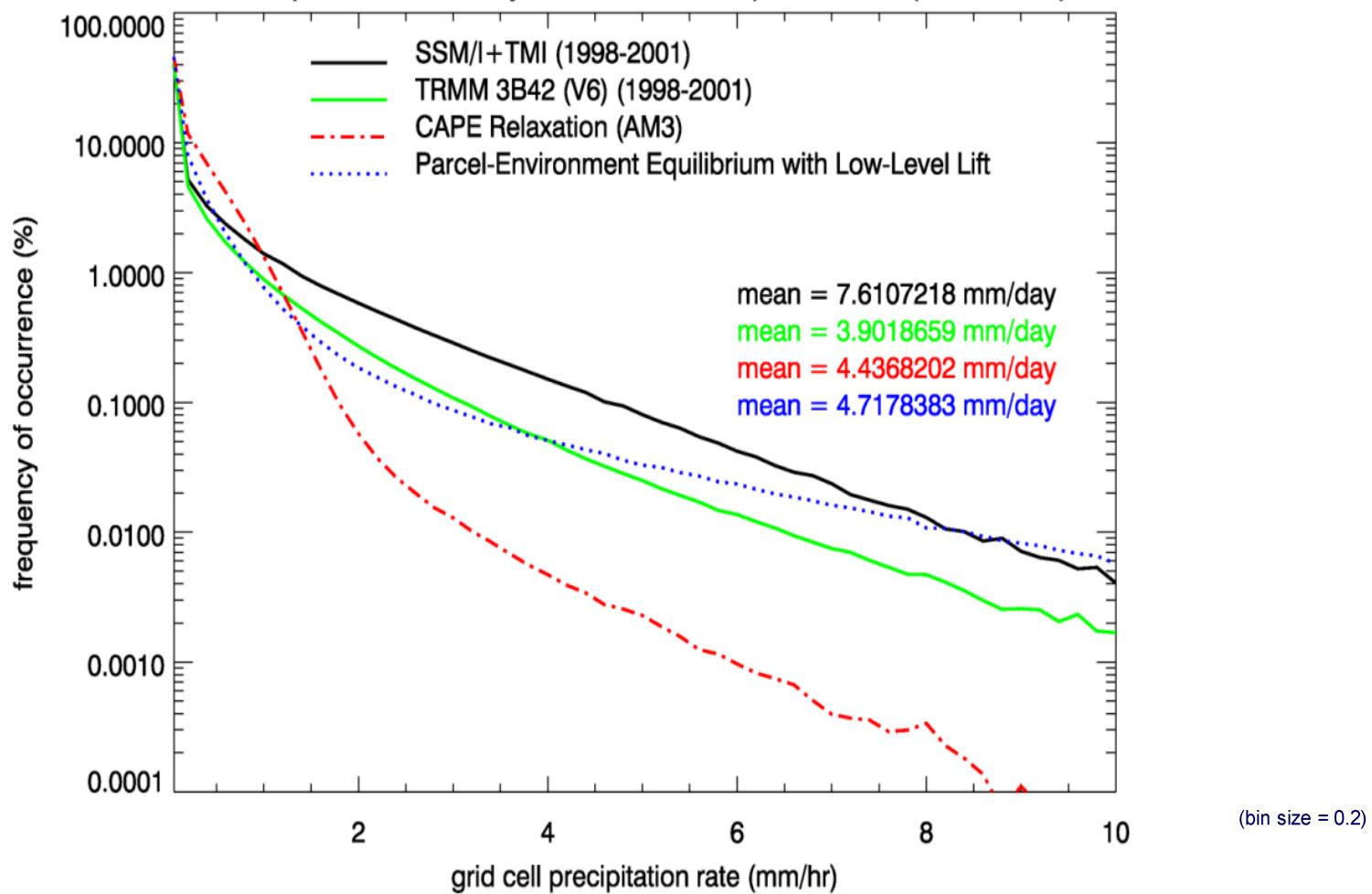
Tropical-Wave Spectrum

Alternate
closure and
trigger for deep
cumulus



from Donner et al. (2011, *J. Climate*)

Precipitation Intensity Distribution Tropical Land (20S - 20N)



Summary

- AM3 deep cumulus parameterization novel in its inclusion of cumulus vertical velocities and mesoscale circulation, with major implications for mass fluxes.
- Deep cumulus interacts other cloud parameterizations
- AM3 has single ITCZ, but CM3 has double ITCZ.
- Current closure produces poor MJO and precipitation intensity distribution, which can be improved with alternate closure and trigger.
Alternate closure increases global-mean precipitation.

AM3 has too much ice in tropics and too little in mid-latitudes.

Anvil ice assumed in equilibrium between convective source and precipitation-yield too much ice.

